CONSTRAINING LV GRAVITY WITH GW OBSERVATIONS

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Based on works with

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2103.00929

- WHY?
- HOW?
- WHAT?

- WHY? We consider LV Gravity.

- HOW? We constrain its parameter space

- WHAT? Is the theory left over

WHY are we interested on Lorentz Violations in Gravity?

- Why not?

Is Nature really Lorentz invariant?

Precision tests in the matter sector
Gravitational physics is mostly tested in the non-relativistic limit
(Local tests in the solar system, large scale cosmology)

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- Quantum Gravity

Hořava Gravity

Renormalizable (at least in some cases)
Can provide a UV completion for GR
Formulated as a standard field theory

WHY are we interested on Lorentz Violations in Gravity?

Einstein-Aether Gravity

EFT approach to Lorentz Violation in Gravity

The vector U sets a universal preferred frame

$$g_{\mu\nu}, U^{\mu}$$

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\left(-R - K^{\alpha\beta}_{\mu\nu}\nabla_\alpha U^\mu \nabla_\beta U^\nu - \lambda(U^\mu U_\mu - 1)\right)$$

$$K^{\alpha\beta}_{\mu\nu} = c_1 g^{\alpha\beta} g_{\mu\nu} + c_2 \delta^\alpha_\mu \delta^\beta_\nu + c_3 \delta^\alpha_\nu \delta^\beta_\mu + c_4 U^\alpha U^\beta g_{\mu\nu}$$

Jacobson & Mattingly, 2000

WHY are we interested on Lorentz Violations in Gravity?

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Three propagating modes

$$g_{\mu\nu}, U^{\mu}$$

$$c_T^2 = \frac{1}{(1 - c_1 - c_3)} \qquad c_V^2 = \frac{c_1 - \frac{c_1^2}{2} + \frac{c_3^2}{2}}{(c_1 + c_4)(1 - c_1 - c_3)}$$

$$c_S^2 = \frac{c_1 + c_2 + c_3}{c_1 + c_4} \frac{2 - c_1 - c_4}{2(1 + c_2)^2 - (c_1 + c_2 + c_3)(1 + c_1 + 2c_2 + c_3)}$$

WHY are we interested on Lorentz Violations in Gravity?

Einstein-Aether Gravity

Three propagating modes

$$g_{\mu\nu}, U^{\mu}$$

- GW propagate at c=1 $\quad c_1 + c_3 = 0$

- Solar system tests $\quad c_1 - c_3 = c_\omega, 3c_2 = c_\theta \leq \mathcal{O}(1)$

- The limit of HG $\quad c_\omega \to \infty$

Foster & Jacobson, 2006
Bonetti & Barausse, 2015
Muller, Williams & Turyshev, 2008
Will, 2006
Carrol & Lim, 2004
Abbott et al. 2017
Horava, 2009

- ~~WHY?~~ ~~We consider LV Gravity.~~

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How do we constraint the parameter space of EA?

- Violations of the strong equivalence principle

In modified theories of Gravity, compact objects do not move on geodesics of the metric

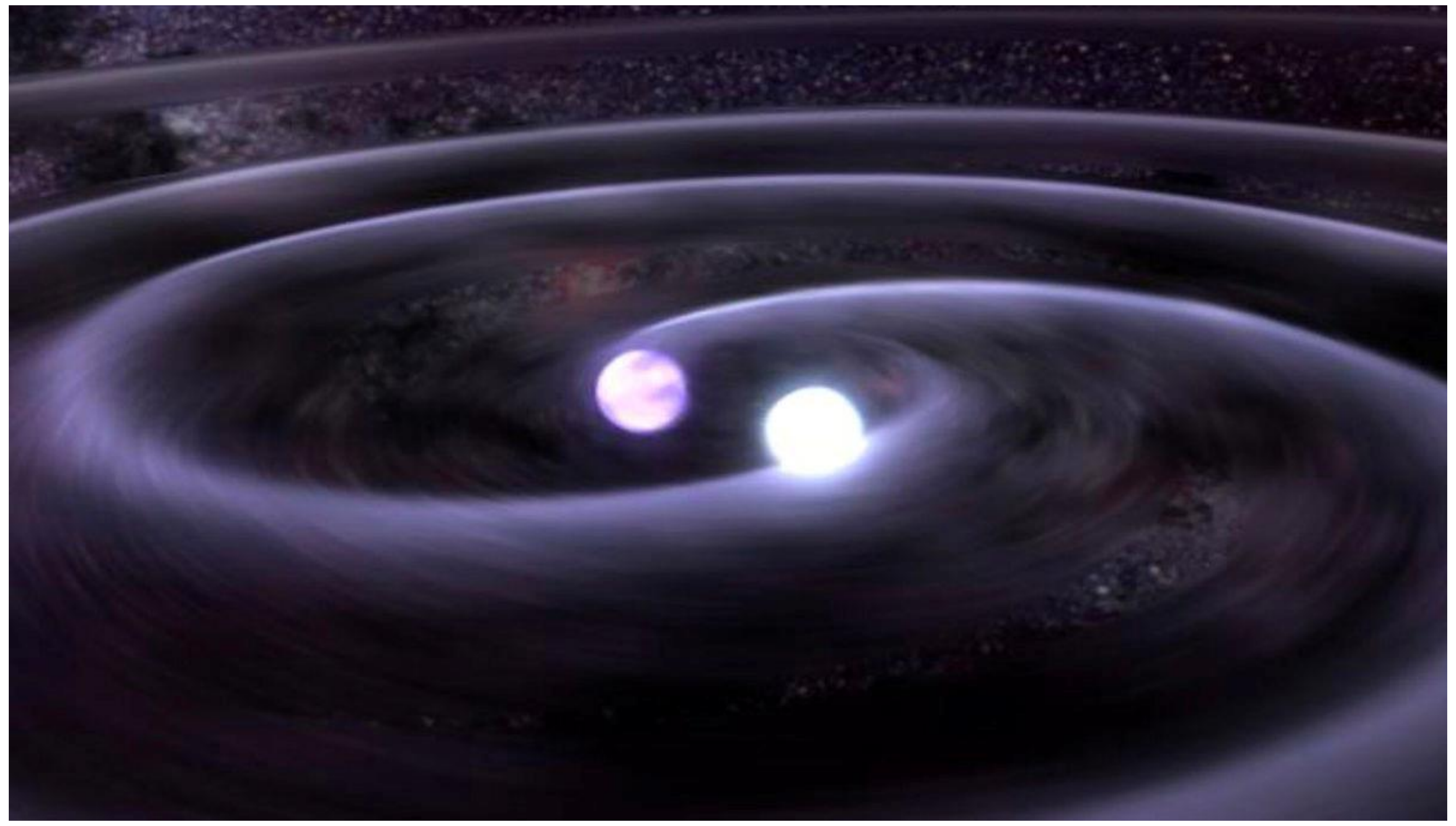
In the point particle approximation this is parametrised by sensitivities

$$S = -\int d\tau m(\gamma), m(\gamma) = m_0[1 + \sigma(1 - \gamma) + \cdots], \qquad \sigma = \frac{\mathrm{dlog} m(\gamma)}{\mathrm{dlog}\gamma}|_{\gamma=1}$$

$$\gamma = u \cdot U = F(c_i)$$

The sensitivities also control the emission of gravitational waves in binary systems of compact objects i.e. binary pulsars

How do we constraint the parameter space of EA?



- As pulsars move the period of the orbit change due to emission of GW

$$\frac{\dot{E}_b}{E_b} = 2\left\langle \left(\frac{\mathcal{G}_{12} G m_1 m_2}{r^3}\right) \left\{ \frac{32}{5}(\mathcal{A}_1 + \mathcal{S}\mathcal{A}_2 + \mathcal{S}^2\mathcal{A}_3) v_{21}^2 \right.\right.$$
$$+ (s_1 - s_2)^2 \left[\mathcal{E} + 2\mathcal{D}[w^2 - (\boldsymbol{w}\cdot\boldsymbol{n})^2] + \frac{18}{5}\mathcal{A}_3\, w^2 + \left(\frac{6}{5}\mathcal{A}_3 + 36\mathcal{B}\right)(\boldsymbol{w}\cdot\boldsymbol{n})^2\right]$$
$$\left.\left. - (s_1 - s_2)\,\frac{24}{5}(\mathcal{A}_2 + 2\mathcal{S}\mathcal{A}_3)(\boldsymbol{w}\cdot\boldsymbol{v}_{21}) \right\}\right\rangle,$$

Foster, 2007
Yagi, Blas, Barausse & Yunes, 2014

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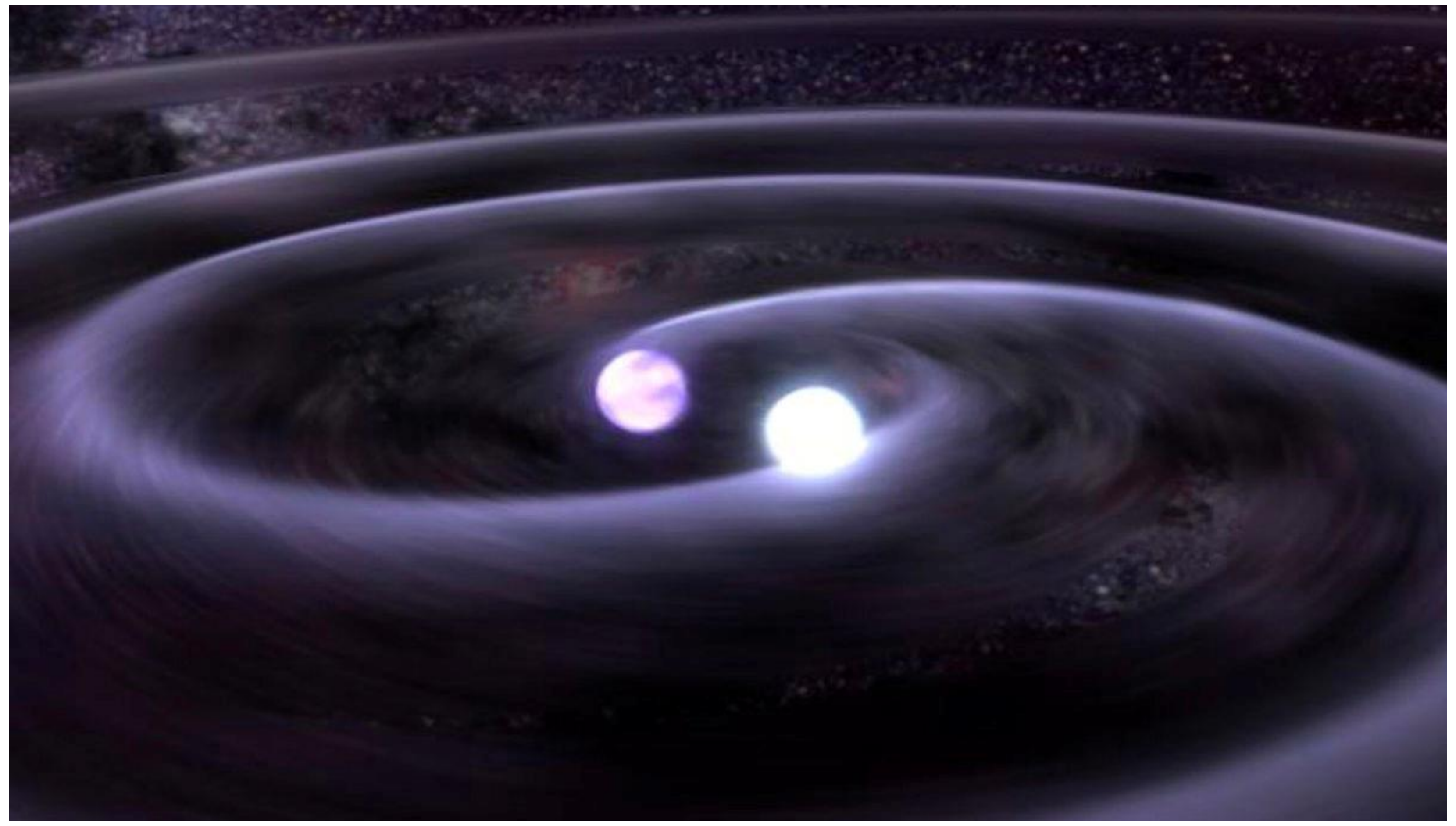

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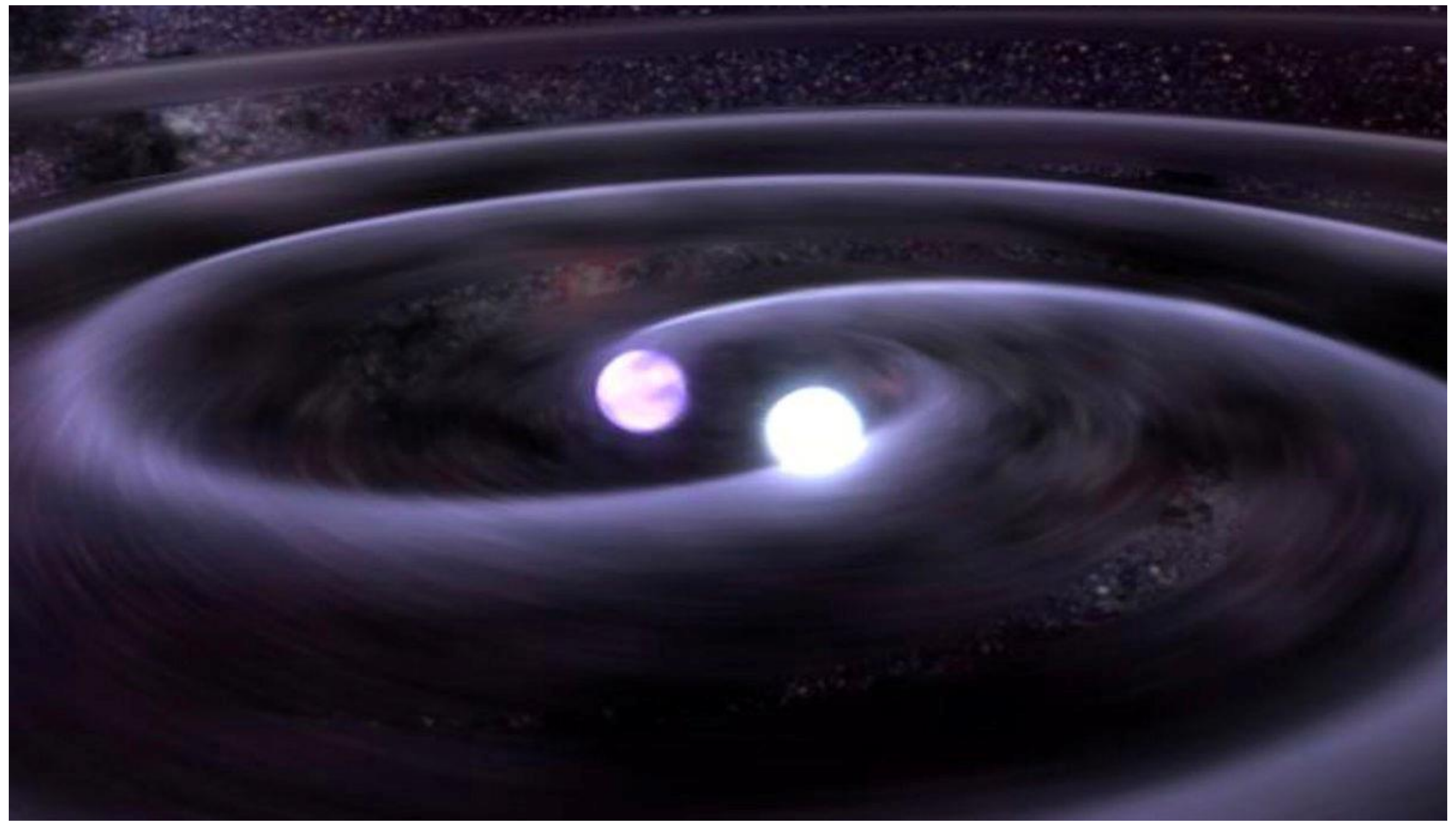

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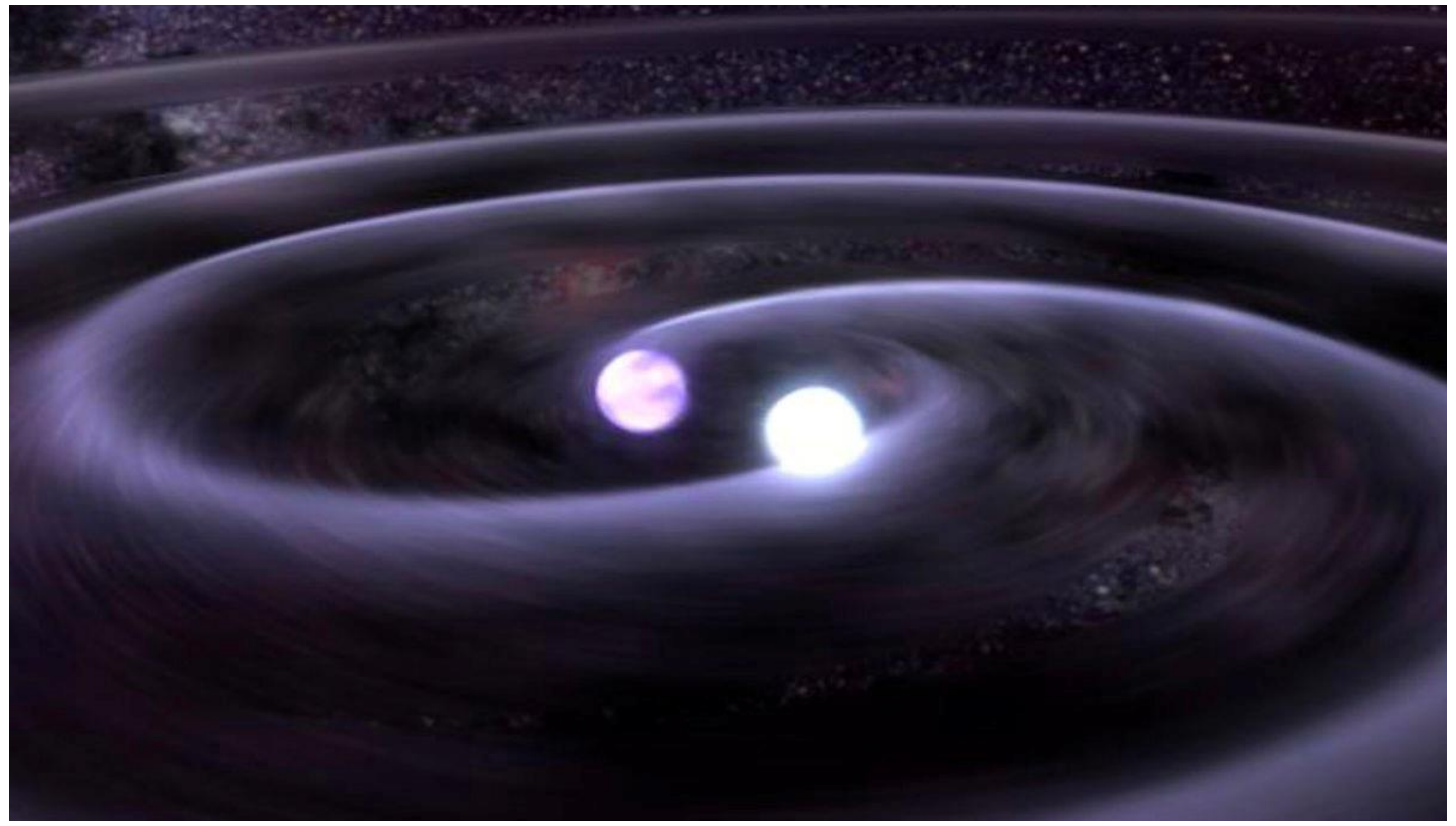

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- However, instead of the c_i couplings, we use a different parametrization

$$\alpha_1, \alpha_2, c_\omega, c_\sigma$$

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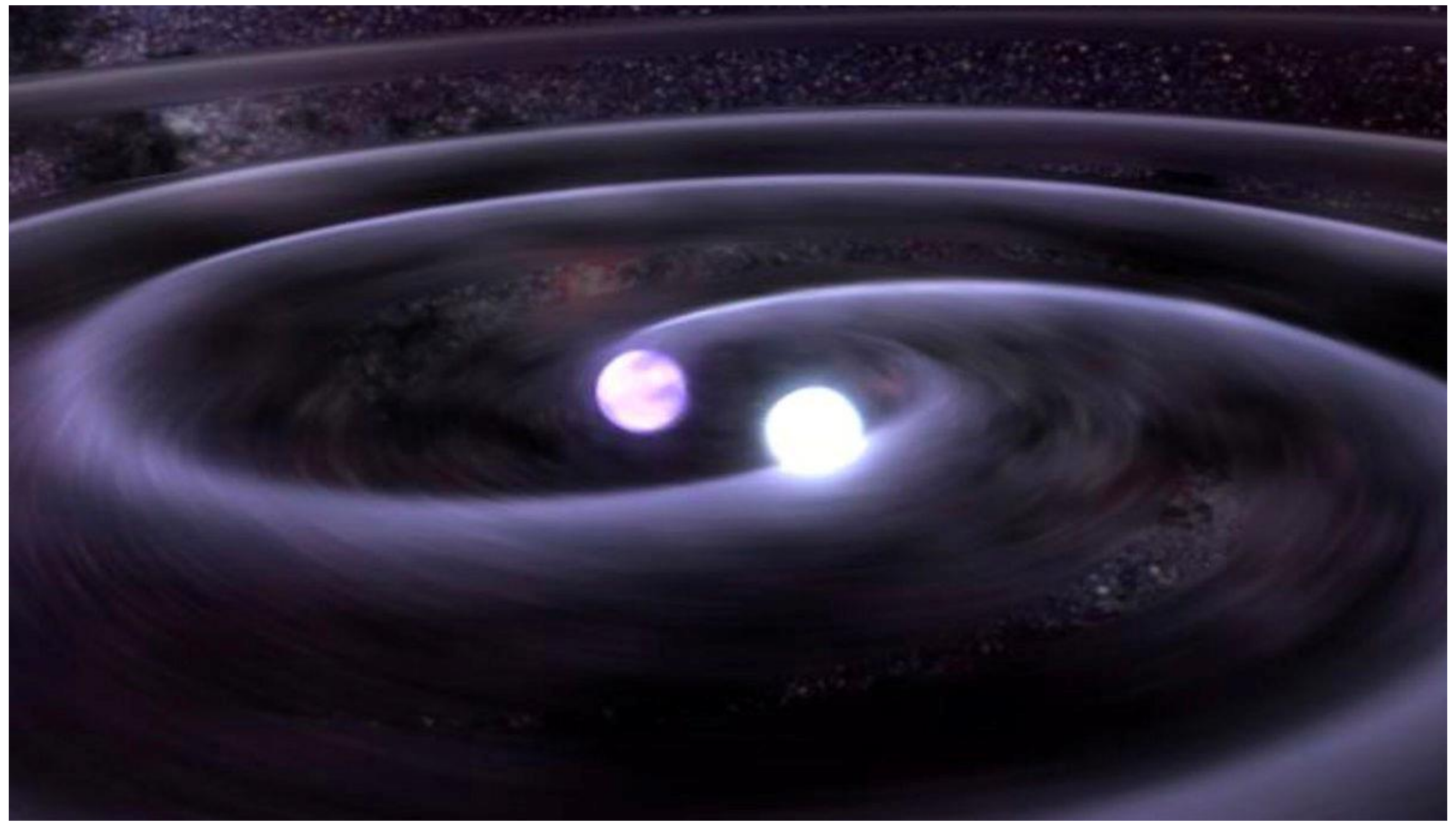

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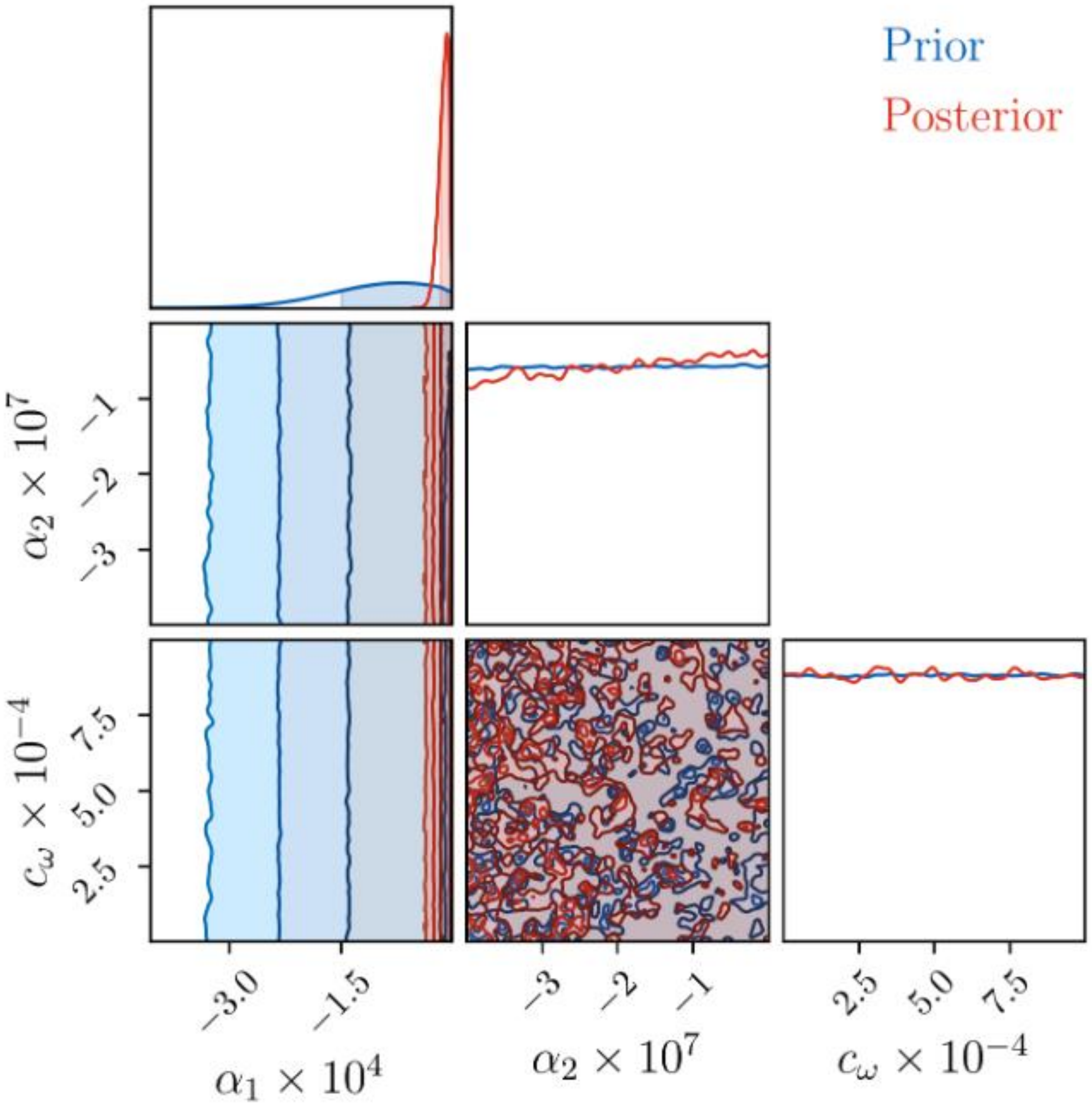
Pulsar System	$m_1(M_\odot)$	$m_2(M_\odot)$	P_b (days)	$\dot{P}_b^{\text{obs}}$
PSR J1738+0333[35]	$1.46^{+0.06}_{-0.05}$	$0.181^{+0.008}_{-0.007}$	0.3547907398724(13)	$-25.9(3.2) \times 10^{-15}$
PSR J0348+0432 [6]	2.01(4)	0.172(3)	0.102424062722(7)	$-0.273(45) \times 10^{-12}$
PSR J1012+5307 [21] [51]	1.64(0.22)	0.16(0.02)	0.60467272355(3)	$-1.5(1.5) \times 10^{-14}$
PSR J0737-3039 [50]	1.3381(7)	1.2489(7)	0.10225256248(5)	$-1.252(17) \times 10^{-12}$

+ triple system PSR J0337+1715


Prior
Posterior
$\alpha_2 \times 10^7$
−1
−2
−3
$c_\omega \times 10^{-4}$
7.5
5.0
2.5
−3.0
−1.5
$\alpha_1 \times 10^4$
−3
−2
−1
$\alpha_2 \times 10^7$
2.5
5.0
7.5
$c_\omega \times 10^{-4}$

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WHAT is left is a version of Horava Gravity

Minimal Horava Gravity (mHG)
Only one coupling left (λ-theory)

U is hypersurface orthogonal

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\Big(-R - \lambda\nabla_\mu U^\mu \nabla_\nu U^\nu - \alpha(U^\mu U_\mu - 1)\Big)$$

Cosmological dynamics is different from GR

Constraint analysis shows that the theory is in general different (but there were claims based on asympotic flatness)

The scalar mode is strongly coupled (not a problem)

Loll & Pires, 2014
Belllorin & Restuccia, 2012
Henneaux & Kleindschmidt, 2010

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Quasinormal modes are independent of λ

Spherical collapse is independent of λ

(non-rotating) Black holes are Schwarzschild (although they allow for extra couplings with U)

CONCLUSIONS

- Lorentz violating Gravity is a possible option for modifying GR
- The parameter space of the theory at low energies is constrained
- A version of Horava Gravity survived and remains possible
- Further constraints seem to require exploring higher energies

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Thank You!